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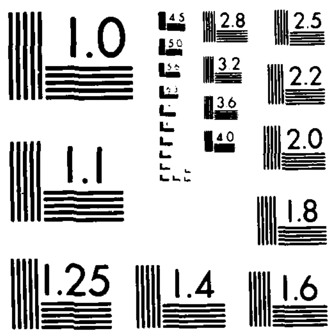

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A COST AND BENEFIT ANALYSIS OF HYDRAULIC FLUID SYSTEMS FOR THE NEXT GENERATION OF TACTICAL AIRCRAFT

THESIS

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Captain, USAF

AFIT/GSM/LSY/87S-18

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THESIS

Presented to the Faculty of the School of Systems and Logistics
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Systems Management

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Captain, USAF

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ACKNOWLEDGMENTS

The purpose of this study was to determine if a new nonflammable hydraulic fluid (CTFE) is a cost effective alternative in future aircraft hydraulic systems. However, before the study my knowledge on hydraulic systems, hydraulic fluids, and other materials was very limited. Therefore, I am very grateful to several people.

On hydraulic systems, I want to thank Bill Kinzig for his patience in providing me with the basics, to thank Bruce Campbell and Ed Binns for providing me information on 3000 psi and CTFE hydraulic systems, and to thank Bill Bickel and John Ohlson for providing me guidance and information on the 8000 psi research conducted for the Navy.

On hydraulic fluids and seal materials, I am grateful for the support given by Lois Gschwender and Carl Snyder. On the economic analysis and the writing of this study, I am deeply indebted to my faculty advisor, Doctor Leroy Gill, for his continuing patience and assistance.

Finally, I wish to thank my wife Pat for her support, understanding and concern during the long hours on the computer. She provided unlimited assistance in helping me take care of my dying mother and allowing me to keep my mind on school. So I dedicate this to my mother and my wife, because without them I would not have completed this thesis.

Michael P. Mahony

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Abstract

This study analyzed the life cycle costs, cost of fires, and benefits of using a new nonflammable hydraulic fluid (CTFE) in future tactical aircraft versus a fire retardant fluid (Mil-H-83282) currently used in tactical aircraft. The study assumed that future hydraulic systems will use 8000 psi pressure. An analogy was made using a McDonnell Douglas Corporation study as the basis. This study compared Mil-H-83282 and CTFE at 8000 psi showing weight as the primary difference. Therefore, this weight difference, the fluid price difference, and the fuel consumption of an F-15 were used to determine the life cycle cost difference between the two systems. Since the added weight was slight, only the additional fuel consumption to fly the extra weight was significant. The added life cycle costs for using CTFE was estimated at $11.4 million in FY87 dollars.

However, CTFE will prevent hydraulic fires so an estimate of Mil-H-83282 fire costs was attempted. These fire costs were difficult to accurately determine. The history of hydraulic fluid contained primarily fires caused by a highly flammable fluid (Mil-H-5606). Also, early fires involving Mil-H-83282 included Mil-H-83282 mixed with Mil-H-5606. Therefore, only a limited history on the true fire

resistance capabilities of Mil-H-83282 was available. Also the available history failed to include several other costs which are incurred when the fire occurs.

The differences in the benefits were primarily in the survivability and capability of the aircraft. Taking these differences together CTFE is slightly better than Mil-H-83282 in peacetime. This difference becomes more pronounced in wartime.

Finally, a sensitivity analysis was conducted on the assumptions. Based on these analyses, a conclusion was made that CTFE was a viable alternative at 8000 psi. However, further research is needed on the logistical problems related to the new pressure and fluid. Also, further study is needed on the effectiveness of Mil-H-83282 against the causes of hydraulic fires.

A COST AND BENEFIT ANALYSIS OF HYDRAULIC FLUID SYSTEMS FOR THE NEXT GENERATION TACTICAL AIRCRAFT

I. Introduction

The purpose of this thesis is to analyze the costs and benefits of using a new nonflammable hydraulic fluid in the next generation of tactical aircraft in comparison to a fire retardant or limited flammable fluid such as that currently being used. In the past, aircraft fires caused by flammable hydraulic fluids have been expensive as Table 1 demonstrates.

Table 1. Hydraulic Fire Loss History (1967 - 1986) (13)

Year	Dollar Loss	# of Mishaps	# of Injuries	# of Deaths
1967 - 1971	$ 67,098,882	48	4	2
1972 - 1976	87,177,227	66	5	3
1977 - 1981	54,719,679	52	5	0
1982 - 1986	20,201,500	67	2	0
Total	$229,197,288	233	16	5

As can be seen from data in this table, the overall average loss due to fires involving hydraulic fluids has been approximately one million dollars per incident (unadjusted for inflation). Approximately half of these fires occurred on tactical aircraft and the most common cause of the fires was due to hydraulic fluid dripping on to hot brakes or other hot surfaces (13).

The above losses encouraged the Air Force to look for a nonflammable hydraulic fluid. However, the nonflammable fluid currently being tested weighs more than the current fluids, costs more than these fluids, and is not compatible with existing hydraulic systems. The focus of the current research is on future aircraft since the cost of converting the hydraulic systems of existing aircraft is quite high. An estimate done by the Materials Laboratory of the Air Force Wright Aeronautical Laboratories (AFWAL) concludes it would cost approximately 1 million dollars to convert a B-52 to use the currently tested nonflammable hydraulic fluid (30).

While the testing continues, the Air Force is replacing on an attrition basis in tactical aircraft the hydraulic fluid which was involved in the majority of previous fires, Mil-H-5606 (highly flammable), with a compatible fire retardant fluid, Mil-H-83282.

Thus, the research in this thesis will focus on the cost and benefits of using the nonflammable fluid versus the current fire retardant fluid.

The next chapter discusses the nature of hydraulic systems, why a nonflammable hydraulic fluid may be needed, how the development has progressed, and the technology needed to implement the nonflammable fluid.

Chapter 3 examines the costs and benefits of using a limited flammable versus nonflammable hydraulic fluid in the next generation of tactical aircraft. The two fluids are compared beginning with their benefits, followed by the life cycle costs (LCC) excluding fires, then the LCC of fires, and then a summary of the total LCC involved in the decision on which fluid to use.

Chapter 4 will test the sensitivity of the analytical results developed in Chapter 3 to the conditions of peacetime and wartime scenarios. Also other major uncertainties involved in the analysis will be examined. Based on the foregoing, conclusions will be made with regard to the use of CTFE and recommendations will be made for future research.

II. History of Advances in Hydraulic Systems

The purpose of this chapter is to explain the nature of hydraulic systems, why a nonflammable hydraulic fluid may be needed, how the development has progressed, and the technology needed to implement the nonflammable fluid.

What is a Hydraulic System?

The information on hydraulic systems in this section is based primarily on information contained in George Keller's book Hydraulic System Analysis (Second Edition) (18). (Technical terms used in this thesis are defined in the glossary of technical terms in the Appendix).

A hydraulic system is based on Pascal's Law of Hydrostatics which states that pressure applied to a fluid will be transmitted through the fluid until it becomes concentrated in an area of least resistance (18). On aircraft, hydraulic systems are used to power essential systems such as landing gear and flight control systems. Figure 1 shows the type and location of hydraulic systems on a typical fighter aircraft. Each hydraulic system can be divided into four areas: power input unit, power distribution system, control devices and power output unit (18). These four areas are discussed in turn:

Power Input Unit. The power input unit involves pumps and accumulators. Pumps are the primary source of power in

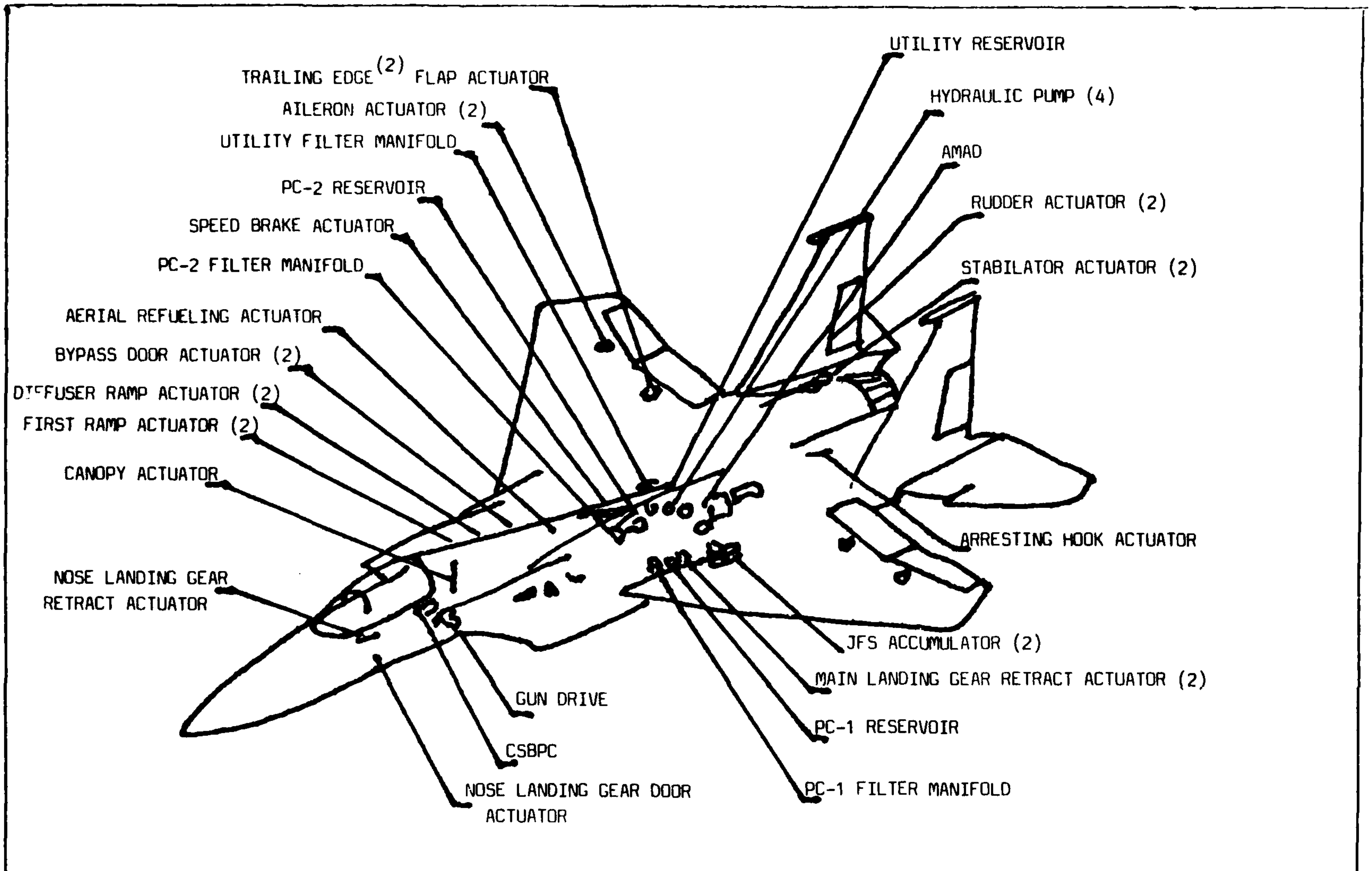

Figure 1. F-15 Hydraulic System Component Locations (17:7)

the hydraulic system. Piston pumps are usually used in high-pressured systems above 2500 psi. These pumps allow the fluid to enter the pumping chamber as the piston retreats and then they force the fluid into the distribution system as the piston returns. However, if not properly designed, a pump can waste power or energy and heat up the system and this can damage the fluid, seals and other organic material in the system. Heat exchangers are used to remove the excess heat from the system before damage can occur (18).

Accumulators store the fluid under pressure. If the system's pressure decreases below the level of the pressure which holds the fluid in the accumulator, then the fluid is released into the system under pressure. Accumulators also supply fluid for temporary demands greater than the pumps can supply (18).

Power Distribution System. The power distribution system connects the other three areas together. It is primarily comprised of reservoirs, tubing, connectors, and seals (18).

Reservoirs. A reservoir provides fluid to make up for system leakage, allows space for expansion due to increases in temperature, allows gas bubbles to escape from the fluid and allows dirt to settle to the bottom. If contamination from dirt is possible or if high operating temperatures (over 200° F) exist, a closed hydraulic system with an airless reservoir is used. The size of the reservoir is based on weight or installation requirements (18).

Tubing. Weight also determines the materials used for tubing in hydraulic systems. When weight is critical, the design must address the effect of stresses in determining the size of tubing and necessary wall thickness. Requirements for the tubing connectors will also have a bearing on choice of materials (18).

Connectors.

> Connectors performs three tasks: the connector must join to the tubing in a firm, leakproof manner; must carry any loads or stresses imposed on it by the hydraulic system or by the tubing, and; must provide a seal between the parts being joined (18:81).

Two primary groups of connectors are classified as either separable or permanent. The former includes at least one joint which can be removed and attached easily (18).

Permanent connectors are attached by welding or brazing. They are more leak-free, reliable, smaller, and lower in weight than separable connectors. However, they require large capital investment, they are harder to inspect (x-rays are required), and they are harder to repair since a specialty shop is needed to make the joint (18).

Seals. To make leak-free connections, a sealing element or device which can be a plastic, elastomer, gasket material, soft metal, or part of the tubing, is used. The efficiency of the seal depends on the design of the sealing element. Pressure on the seal can either increase the effectiveness or cause the seal to fail (18).

There are three types of seals: static, dynamic and rotating. Static seals use a pressure level significantly higher than the system pressure they must contain to seal with their mating parts. Dynamic seals must withstand motion as well as contain the systems pressure. Rotating seals are used around a rotating shaft. "A combination of pressure and spring force causes two carefully mated parts to bear on each other with relative rotary motion and create a very fine fit" (18:145).

> Elastomers are seals which incorporate the aspects of solid materials and those of very high viscosity fluids. Under pressure they flow and deform until internal stresses equal the external. This flowing action is similar to the flow of highly viscous fluids (18:140).

If the clearance between the mating parts is small, the elastomeric seal may extrude. As pressures increase over 1500 psi, extrusion is unacceptable and backup seals are used to correct the extrusion. The backup seals reduce the clearance (18).

<u>Control Devices</u>. Seals connect control devices to the system. Control devices include relief valves, pressure control valves and flow control valves. Relief valves are usually used to limit pressure surges or to compensate for failed pump pressure controls. The basic design uses a spring whose tension provides a reference to determine if

"the valve needs to open and allow flow from the high pressure region to the low pressure region" (18:78).

Pressure control valves (or regulators) are used to lower the pressure in a portion of the system to a desired level. Some examples of these valves include: pressure reducing valve, lack pressure regulators, and differential pressure regulators (18).

Flow control valves perform two primary functions: they direct the flow of fluid from power generating devices and distribution systems to power transducers and they use the system's pressure to restrict the fluid flow. Flow control valves can be classified as either shutoff or modulating valves (18).

Power Output Unit. Power output transducers are the final part of the hydraulic system. This part consists of linear actuators and rotary or oscillating motors. The primary hydraulic system motors are cylindrical actuators which provide or develop a straight line motion. These actuators are called linear actuators (18).

Actuators. Actuators can be balanced, unbalanced or partly balanced in terms of fluid used in extension versus retraction of the rod within the cylinder. Actuators may be designed in tandem or parallel to provide multiple alternatives for hydraulic systems for added reliability of the overall system. The tandem design requires a balanced actuator, while the parallel design can use all three types of balancing in an actuator (18).

Basic design parameters for linear actuating cylinders include the "determination of the working area of the piston, the sizing of the rod, and the choosing of the proper inside diameter and wall thickness of the cylinder housing" (18:126).

Motors. The most common oscillating motor in an hydraulic system is a vane motor. It is very compact. The motor can have several vanes which increases the output torque capability (18).

Rotary motors are used in the pumps previously discussed. This type of motor is "specified when the load must be continuously rotated, as in a radar drive, or where stroke length or accuracy requirements preclude the use of linear actuators" (18:135).

History of Hydraulic Systems

The first airborne hydraulic system was developed in 1937 because higher performance was demanded and this involved the use of larger landing gears, brake systems, flaps, and bomb doors. The previous systems which worked electrically or pneumatically, became unreliable and dangerous with this increased demand. Early hydraulic systems had a self-contained set of circuits and used mineral oil which was energized by engine-driven pumps and controlled by electrically-operated valves. These early systems were able to operate at pressures of 800 to 1000 psi. In 1939, the O-ring seal was developed and this allowed pressures to increase to 3000 psi (15).

The hydraulic systems on an aircraft today are used to operate devices which require high power, quick action and accurate control. The number of devices has continually increased over the years and so has the amount of power required to operate these devices. The power required on the F-15 is 400 horsepower and future aircraft are projected to need at least 800 horsepower (27;30).

The needed increase in power is caused by higher aerodynamic loading on control surfaces which result from increased aircraft performance, and expanded hydraulic functions which include engine and thrust control concepts. As aircraft designs attempt to reduce drag and conserve fuel, and mission capabilities continue to expand, the internal volume or space available for subsystems decreases. In addition a smaller percentage of weight is allocated to hydraulic systems. Therefore, since higher pressure hydraulic systems exert more force for a given volume (and weight) of fluid, improvements in hydraulic system efficiency using engineering concepts for 8000 psi are being developed (3).

The use of 8000 psi is projected to reduce the weight and volume of the hydraulic system without impacting the reliability of the system. This reduction in weight would increase the range or sortie length of the aircraft because the fuel consumption would decrease. The reduction in volume would improve the survivability of the aircraft. The maintenance man-hours would be reduced due to fewer components and better technology. Moreover, increasing the pressure of hydraulic systems does not necessarily decrease reliability if high quality components are used (3;17).

The Need for a Nonflammable Fluid

Hydraulic systems have grown in usage since their introduction to aircraft systems. Hydraulic systems have proven to be durable, maintainable, and efficient. These qualities have encouraged the extensive use of these systems in all parts of the aircraft. However, the proliferation of hydraulic systems has made aircraft highly vulnerable to hydraulic fluid fires due to normal wear and tear, maintenance error, pilot errors, or combat damage (28).

Hydraulic fluid fires have been a problem since the fluid was first used in aircraft because of the fluid's flammability. The Air Force, since 1965, has lost an average $14 million a year (unadjusted for inflation) due to aircraft damage or loss related to hydraulic fires (13).

Losses from hydraulic system fires have been increased by the widespread use of Mil-H-5606 which is a mineral-oil based fluid and is highly flammable. The use of this fluid has been based on the fact that its operational advantages outweigh its disadvantages. However, as the operating requirements have become more demanding and the proliferation of the hydraulic systems in aircraft continues, the need for a nonflammable fluid has grown (28).

Historical Search For a Nonflammable Hydraulic Fluid

Research for a functional, nonflammable fluid began in the 1950's but these early fluids could not meet the necessary operational requirements of the aircraft. Thus, the military and commercial aircraft industry accepted some flammability because the benefits outweighed the risks (28).

In the 1950's the commercial aircraft industry "introduced phosphate ester hydraulic fluid (Skydrol) along with the required compatible hydraulic systems" (28:1). Skydrol was less flammable than the hydraulic fluids previously used. However, the military did not adopt this fluid because it was not compatible with the hydraulic systems in the military aircraft at the time. Also, the military felt that:

> the use of two incompatible hydraulic fluids could not be supported logistically and could result in significant problems if the two fluids were ever inadvertently mixed (27:1).

In the 1960's AFWAL/MBTL developed Mil-H-83282, a hydrocarbon hydraulic fluid. This fluid is more fire resistant than the Mil-H-5606 thus reducing the threat of fires in aircraft. The Navy and the Army were the first to introduce Mil-H-83282 into their hydraulic systems. Since its gradual introduction, the number of fires have been reduced. Introduction of this fluid into existing systems required no material or design changes. In fact, it has been added to the current fluid, Mil-H-5606, on an attrition basis (28). Although Mil-H-83282 fluid has the advantage of being fire retardant, the Air Force was reluctant to use Mil-H-83282 due to its main weakness which is its inability to perform well at low temperatures (high viscosity below -45° F). The Air Force finally introduced the new fluid in the early 1980's but Strategic Air Command aircraft and other aircraft flown in cold weather environments were exempted. These aircraft still use the more flammable fluid, Mil-H-5606. Thus, the need for a nonflammable fluid capable of use in cold weather still remains (28).

Table 2 provides a chronological summary of the usage periods for various hydraulic fluids previously discussed. The table shows the movement to less flammable fluids.

Table 2. Chronological List of Fluid Used (28)

Period	Type of Hydraulic Fluid Used by the Military
1950's	Mil-H-5606 (Military-Flammable)
1960's	Mil-H-5606 & Mil-H-83282 (Army & Navy-Fire Retardent)
1970's	Mil-H-5606 (Air Force) & Mil-H-83282 (Army & Navy)
1980's	Mil-H-5606 (Air Force) & Mil-H-83282 (All Military)

With the ultimate goal of nonflammability not being met, research continued to try to develop a nonflammable fluid. One research problem was to develop a nonflammable fluid to use in current hydraulic systems. However, the current hydraulic systems were designed for hydrocarbon oils which are quite flammable. The nature of the oils forced this approach to be abandoned after unsuccessful attempts by AFWAL, the Navy, and the industry over the years. Therefore, halogenated oils of several types which offered the desired degree of fire resistance were analyzed. These oils, however, are not compatible with hydrocarbon oils because of differences in their physical and chemical properties (28).

Based on these problems, General William J. Evans, the commander of Air Force Systems Command (AFSC), eliminated the compatibility requirement in 1975 so that a "truly nonflammable hydraulic fluid" system could be developed for future aircraft (31:3). This new system requires the designing of all components and compatible seals for this nonflammable fluid (23).

Development of a Nonflammable Fluid

Identification of CTFE Fluid. Based on General Evans'decision, a working group was formed to develop the nonflammable hydraulic fluid and related systems. This working group consisted of AFWAL's Materials Laboratory, Aero Propulsion Laboratory, and Flight Dynamics Laboratory, ASD's Flight Systems Engineering Directorate's Mechanical Branch and Fuels Systems Branch and University of Dayton Research Institute personnel. To start the research the Aero Propulsion Laboratory hired the Boeing Military Aircraft Company "to study and select a nonflammable hydraulic fluid for possible use in future Air Force aircraft" (31:3). This study picked two nonflammable fluids as candidates for further study, chlorotrifluoroethylene (CTFE) and Freon E6.5 fluorinated ether. The latter was subsequently eliminated since the projected price and investment cost to produce it were unacceptable (26).

Determination of Fluid Flammability. Carl E. Snyder, Jr., Arthur A. Krawetz, and Theodore Tovrog of the Materials Laboratory examined the flammability of various hydraulic fluids including the CTFE fluid identified by Boeing (26;31). Other fluids involved in the testing included MIL-H-5606, MIL-H-83282, phosphate ester (Skydrol), the Navy-developed silicone, and AFWAL-developed chlorofluorocarbon.

Aspects of flammability tested included the following:

1) Flash and fire points tests. The flash point is the minimum temperature that the bulk fluid must attain to generate sufficient vapor to be ignited by a low-energy flame in a test apparatus. The fire point is the minimum temperature which the bulk oil must attain for ignition and continued burning in a test apparatus (26:706).

The flash point/fire point data have limited usefulness because they are based entirely upon creation of vapor, and are obtained under highly controlled conditions (1:4).

2) Autogenous Ignition Temperature (AIT). This temperature is considered to be the minimum for a fluid to ignite in a test apparatus without an external ignition source (26:706). "The primary usefulness of the test is to furnish a relative rating scale, rather than produce absolute values which can be directly applied to problem solutions" (1:5).

3) Stream Hot-Manifold Ignition Temperature. This test is considered to simulate the fire hazard presented when a fluid comes in contact with a heated surface. This ignition mode is of significant importance in aerospace applications, primarily hot brakes scenarios (26:706).

4) Heat of Combustion. This test measures the heat generated by a fluid during combustion once ignited and is a significant factor in the flame propagation characteristics of a fluid. "The higher the heat of combustion, the greater the energy released into the bulk fluid. This increases the fluid temperature and makes it more easily ignited" (26:706). This heat can raise the temperature of a fluid to its flash or fire point (26:706).

5) Gunfire Resistance. This method consists of the shooting of 50-caliber armor-piercing incendiary ammunition into partially filled aluminum canisters of the

test fluid. Five shots are fired and the number of ignitions and severity of the subsequent fires are reported (26:706-707).

6) Flame Propagation. Flame propagation is an expertimental method:

> to determine differences in flame-propagation characteristics of aerospace hydraulic fluids. These differences can determine whether an aircraft is totally lost or merely slightly damaged (26:707).

Flammability Conclusions. The results of these flammability tests are shown in Table 3. However, the authors qualified their results by saying that these tests were carefully controlled but extrapolation of the results to describe performance under actual conditions must be done with extreme caution. Nonetheless, these results are the only means available to assess the probability of a successful performance (26:708).

With regard to the flash point results higher temperatures indicate that the fluid is less flammable. As shown in Table 3, the currently used fluids have the lowest flash points. In fact, Mil-H-5606 has a flash point within the operational temperature range required for the next generation of aircraft (-65° F to +350° F) and phosphate esters' flash points are just above the upper boundary of the operational range. These low flash points eliminated them from consideration for testing as a nonflammable fluids (5).

Table 3. Results of Hydraulic Fluid Flammability Testing (26)

Parameters:	Flash Point	Auto Ignition	Hot Manifold	Combust. BTU/lb	Flame Propagation
Goal:	n/a	>1,300 F	>1,700 F	<5,000	no reaction
Fluids					
Mil-H-5606	210	435	800	18,100	sustains
Mil-H-83282	435	650	600	17,700	sustains
Phosphate Esters	360	950	1,440	12,800	extinguishes
Silicone	540	770	900	9,740	extinguishes
CTFE	none	1,190	1,700	2,390	no reaction

None of the fluids met the autogenous ignition goal but CTFE was the closest. Also this fluid was the only one which met the hot manifold and combustion goals. The hot manifold test approximates the most common cause of hydraulic fires, hot brakes. When the fluid strikes the hot brakes, a fire usually starts (26:708).

Thus, CTFE was the overall best fluid in terms of nonflammability. The phosphate-ester based fluid used in commercial aircraft was next. It showed excellent ratings except for flash and fire points. However, it tends to decompose at temperatures above 180^{o}C, and it has unique physical and chemical properties which require a specially designed hydraulic system and different materials. Also the silicone fluid showed only a slight improvement over MIL-H-

83282, which in turn showed only a slight improvement over the most flammable, Mil-H-5606 (26:708).

Thus, the work of Boeing and the Materials Laboratory resulted in the CTFE fluid being selected in 1975 as the primary candidate by the working group for further research (31:2-3).

Devel pment of Technology for CTFE

Although it is nonflammable, CTFE is costly, heavy at current system pressures, and require component development. To correct these problems, research continues in order to develop technology which can effectively use CTFE.

A chronology of research areas is presented in Table 4. As shown, the research has been going on for many years and will continue far into the future.

Table 4. Summary of CTFE-Related Development

CTFE Fluid	1970 to present and continuing
8000 psi System	1966 and continuing
CTFE/8000 psi Seals	1976 and final report due in 1987
CTFE/8000 psi Pumps	1980 and final report due in 1987
CTFE/8000 psi System	1980 and continuing

Developing 8000 PSI Technology

Navy and Rockwell Studies. The idea of using 8000 psi in a hydraulic system to reduce the weight of an aircraft is not new. The Navy Research and Development Center and Rockwell International Corporation have been studying the use of 8000 psi since 1966. Their studies involved ten initial phases: the first phase was to test the feasibility of using higher pressures, up to 20,000 psi. As a result of this testing they discovered that operating pressures up to 9000 psi were feasible. The second phase of testing involved using a mathematical model and laboratory tests to "examine trends observed at lower pressures and gain operating experience with pressures up to 9000 psi" (8:6). The third phase was to verify the results of the mathematical model using pressures between 6000 and 9000 psi. The fourth phase tested hardware performance which resulted in the selection of 8000 psi as the operating pressure level for the lightweight hydraulic system (LHS) program. Using 8000 psi LHS design criteria was developed and analyzed to determine weight and volume savings in reference to an F-14. The fifth through the ninth phases involved the design and testing of 8000 psi components in detail. The tenth and last initial phase was to conduct further endurance testing on the 8000 psi components from the seventh phase. The researchers felt the most important components in an aircraft hydraulic system are the pumps and seals. The last endurance testing showed the pump and seal performance to be highly satisfactory. The pump was modified so future pumps could perform better. The seals were standard, off-theshelf materials which would minimize conversion costs from 3000 to 8000 psi (8;9).

The next area of testing involved the use of the A-7E to continue the LHS development program. This portion includes three phases which began with the design and testing of 8000 psi components for the A-7E, followed by testing these components in a simulator, and ending by conducting flight tests of the components (4).

The above program was initiated because researchers predict that the next generation of tactical fighters will have hydraulic power requirements much higher than current aircraft. This high requirement is due to "increased aircraft performance, and expanded hydraulic functions which include engine and thrust control concepts" (3:2). The new airfoil designs and expansion of mission capabilities have reduced the internal space available for the hydraulic systems. Thus, the need to reduce the weight and size of the hydraulic systems (3).

McDonnell Douglas Study. In addition to the 8000 psi research of the Navy Research and Development Center and Rockwell International Corporation, research has also been conducted by the McDonnell Douglas Corporation. ASD hired McDonnell Douglas Corporation in 1981 "to determine the technology required to utilize the CTFE fluid in aircraft systems with a minimum weight penalty and assurance of acceptable performance" (7). Their final report, dated

December 1984, stated that the CTFE weight penalty can be corrected by using 8000 psi and other engineering concepts. As a result of using 8000 psi, the F-15 hydraulic system fluid volume was reduced from 23 gallons to 9.7 gallons. The use of 8000 psi resulted in significant weight and fuel savings. Using an F-15C as a baseline system, these savings were put into two cost models (RCA Price and McDonnell Douglas' Advanced Concepts Cost Model) in order to estimate the possible life cycle cost savings from using 8000 psi. According to the cost models estimates, the life cycle costs for 500 aircraft over 15 years can be reduced by at least $137 million if 8000 psi is used (17).

Other CTFE Research. In order to use CTFE fluids a number of advances in hydraulic technology are required in the areas of 8000 psi pressure, hydraulic seals, hydraulic pumps, etc. The research planned or in progress in these areas follows.

Seal Development for CTFE. Since 1976, the AFWAL Materials Laboratory and TRW, Incorporated, have worked to develop material which is compatible with the nonflammable fluid. The early research had successfully developed seal materials for 3000 psi and temperature range from -65° F to +275° F. More recent research by TRW, according to Carl E. Snyder, Jr. and Lois Gschwender, has developed at least two primary candidate seals for 8000 psi (29).

Pump Development. Vickers Incorporated won an ASD contract "to develop a 40 gallons per minute 8000 psi/CTFE fluid pump" (7:1). McDonnell Douglas was contracted by ASD "to analyze, design, develop and demonstrate energy management techniques for reducing the power requirements and size of aircraft hydraulic systems" (7:1). The concepts have been identified, components fabricated, and testing has started in all cases, with satisfactory progress (7:1).

Future Development. A number of initiatives are presently under way. In April 1987, McDonnell Douglas Corporation won a contract to develop and demonstrate the feasibility of the 8000 psi/CTFE fluid technology created during previous Air Force, Navy and contractor sponsored programs for use in future aircraft. Another contract will be awarded to study means of improving mean wear-out times for 8000 psi hydraulic system components. Additionally, a contract will be awarded for the design of smaller actuator systems which can meet the requirements of advanced flight control concepts (7:2).

Summary

The military has been looking for a nonflammable hydraulic fluid since the Viet Nam War demonstrated the vulnerability of aircraft to hydraulic fires. This type of fires has continued because of the inability to find a nonflammable fluid which can be used in the current aircraft without major retrofitting costs. Therefore, the Air Force has decided that the next generation of aircraft will use the nonflammable hydraulic fluid, CTFE, if cost effective.

The efficient use of CTFE requires a system pressure of 8000 psi. The results of the Navy's research and the McDonnell Douglas study show that 8000 psi can save weight and life cycle costs of the total aircraft. William Bickel and John Ohlson, authors of the Navy report, stated that high pressure hydraulic systems could be successfully operated at these elevated pressures by applying existing analytical and design practices without major advances in the state-of-the-art. This is based on hardware testing and flight testing using an F-14 and A-7E simulator which experienced no major technical problems (3;4;17).

Having considered the nature of hydraulic systems and the search for a nonflammable hydraulic fluid, the next chapter will examine the relative costs and benefits of the nonflammable fluid which has been selected, CTFE.

III. An Assessment of Comparative Benefits and Costs

This chapter examines the costs and benefits of using a limited flammable versus nonflammable hydraulic fluid in the next generation of tactical aircraft. First, the benefits of the two fluids will be compared. Second, their life cycle costs (LCC) excluding fires will be considered. Third, the LCC of fires will be addressed and finally, the total LCC differences will be summarized. Chapter 4 will place the estimated benefits and costs in perspective and make recommendations.

The Problem

The problem as discussed in Chapter 1 is to assess the benefits and costs of the nonflammable fluid (CTFE) relative to those of the fire retardant fluid (Mil-H-83282). Although the CTFE fluid is nonflammable, it weighs twice as much as Mil-H-83282, costs ten times as much, and is totally incompatible with the current hydraulic systems.

The Alternatives

1. Use an hydraulic system with Mil-H-83282 fluid at 3000 psi.

2. Use an hydraulic system with the CTFE fluid at 8000 psi.

The Assumptions

1. The operating pressure for the hydraulic system will be 8000 psi for future aircraft. This assumption is based on a statement made by the commander of AFWAL at a kickoff meeting of a new research contract with McDonnell Douglas Corporation and statements made by Naval researchers on the same subject (3;21).

2. Due to the nonavailability of data on the next generation of tactical aircraft, information concerning the F-15, the baseline aircraft, will be used to project life cycle costs and potential benefits.

3. The costs related to the use of 8000 psi in the aircraft hydraulic systems are assumed equal for both alternatives.

Considerations With Regard to the Benefits and Costs

Benefits. A benefit is whatever "defense" is produced by an Air Force activity. A cost is the money spent to produce that activity. Using these definitions of benefits and costs, it is neither necessary nor correct to identify cost savings as benefits. Cost savings are explicitly measured when the costs of one alternative are compared to those of another.

The benefits of limited flammable versus nonflammable fluids are manifested in their relative improvements in the mission effectiveness of the aircraft. The mission effectiveness is demonstrated by the improvement in the aircraft's availability, reliability, capability and survivability.

Availability. Availability is the percentage of time the aircraft is in service or available for service. As a result of using 8000 psi, the McDonnell Douglas Corporation (MCAIR) study on the F-15C showed between a 15.9% to 18.8% improvement in maintainability based on a comparison with actual data for an F-15 using calendar year 1980 as the baseline. The estimated improvement is caused by the use of a type of motor which reduces the number of components (17). However, the normal preventive maintenance of the aircraft would remain the same for each fluid. This is because the maintainability of an aircraft is a function of the design and testing stages of the acquisition and is not a function of the fluid, according to William Bickel of Rockwell International Corporation and John Ohlson of the Naval Air Development Center (3).

Nonetheless, although normal maintenance would not be affected by the type of hydraulic fluid, the elimination of hydraulic fires by using CTFE would reduce the time lost for repairing fire damage. This reduction would mean that the aircraft would be available for service at a higher percentage with CTFE versus Mil-H-83282.

Reliability. Reliability is the "probability that a system or product will perform in a satisfactory manner for a given period of time under specified operating conditions" (2). Thus, the elimination of hydraulic fires would improve the aircraft's reliability directly and indirectly based on reduced damage within the hydraulic system and other subsystems usually affected by the fires. Also, the operating temperature range is increased slightly on the low end with CTFE. Therefore, CTFE would improve the reliability of a system in colder weather.

Capability. The capabilities of an aircraft are determined by its design and the installed equipment. Both of these are affected by the weight of the aircraft. Since CTFE weighs more, it has a major impact on the aircraft's capabilities. The MCAIR study on the F-15 SMTD (Short Take-off and Landing and Maneuvering Technology Demonstrator) estimated that the CTFE system would weigh from 70 to 95 pounds more than the Mil-H-83282 system (6). This weight equates to an added 260 to 350 pounds* in takeoff weight. The Mil-H-83282 system aircraft could use this added weight to carry: added fuel for greater range, added armament to inflict more damage on the enemy, added avionics to increase its survivability or detection of the enemy, etc. The lower weight would be useful in increasing the speed and maneuverability of the aircraft. All of these would increase the aircraft's mission effectiveness. Nonetheless, the use of

* This is based on the assumption that one pound added to a subsystem will increase takeoff weight by 3.7 pounds due to the additional fuel required to maintain the same flying capability (19).

CTFE would reduce the vulnerability to gunfire and would allow the aircraft to enter higher risk areas in battle.

Survivability. The survivability of the aircraft is one of the most important attributes of CTFE. It is the ability of the aircraft to either complete a mission or return to base with damage or malfunctioning equipment. In a wartime environment where the enemy has greater numbers, it is essential to do the most with the aircraft available. In fact, the search for a nonflammable fluid was driven by the large losses of aircraft and aircrews in Viet Nam.

In the studies by Rockwell International Corporation, the reduction in the hydraulic system's volume caused by using 8000 psi resulted in "a 39.7% reduction in the probability of kill factor for the aircraft flight controls" (3:7). Add the fact that the CTFE system can use smaller lines and the kill factor becomes even smaller.

Mission Effectiveness. All of the above benefits are summarized in Table 5. The nonflammability of CTFE improves the availability, reliability and survivability of the aircraft and aircrews. However, the magnitude of the peacetime differences in benefits attributable to fewer fires is small because the fire history of F-15s with the alternative fluid Mil-H-83282 is excellent: in fact there have been only two fires since 1980. Both fires were considered minor incidents since the number of days lost due to fire damage was small and there were no assets lost. On the

Table 5. Comparison of the Benefits of CTFE Relative to Those of Mil-H-83282.

Benefit	Advantage of CTFE
Availability	
Time Loss for Hydraulic Fire Damage	No Time Lost
Maintainability	Same
Reliability	
Hydraulic System	Better
Other Subsystems	Better
Capability	
Speed	Less
Distance	Less
Maneuverability	Less
Flexibility in Missions	Less
Additional Equipment (i.e. Avionics)	Less
Survivability	
Aircraft	Better
Aircrews	Better

negative side, the added weight of CTFE reduces the aircraft capabilities, but only slightly because the weight penalty is minor. The weight increase attributable to CTFE reflects only the weight and density of the fluid and not additional equipment or design. The added takeoff weight is less than one percent of the total aircraft weight (350 pounds out of 43,200 pounds in gross weight (6)). In conclusion, taking all these effects into consideration, CTFE improves the overall effectiveness of the aircraft and its crew.

Costs. The costs of the alternatives will be analyzed using a life cycle cost (LCC) format. Life cycle costs include research and development costs, investment costs, and operating and support costs. The operating and support cost impacts of using a nonflammable fluid are estimated over the anticipated 15 year operational life of the aircraft. Since the actual operational costs related to the use of 8000 psi and CTFE are unknown, many of the costs used in this analysis were estimated using the contractor's parametric cost models, analogies to present systems, and expert opinion.

The costs were calculated as if the investment decision would be made in 1987 with the production of the aircraft beginning in 1987 as well. Therefore, all dollars are in current dollars and future expenditures were converted into current dollars by the discounting or present value method.

Sources of Life Cycle Cost Information. The life cycle cost information available on the use of 8000 psi and the two fluids was limited to three studies. The three studies were the Grumman Corporation study which looked at Mil-H-83282 at 3000 and 8000 psi in an F-14, a MCAIR study which used Mil-H-83282 at 3000 psi and CTFE at 8000 psi in an F-15C, and a second MCAIR study which looked at Mil-H-83282 and CTFE at 3000 psi and CTFE at 8000 psi in the F-15 SMTD (3;6;17).

The Grumman Study (3). The Grumman Corporation study was completed in 1979. The Navy selected Grumman to retrofit an F-14 using an 8000 psi hydraulic system to determine the weight and volume improvements from using the higher pressure. Grumman began by establishing the performance and mission requirements, then used a computer program to develop an 8000 psi aircraft configuration. Based on this configuration and in comparison to the baseline configuration, the company estimated weight, volume and related LCC savings using internal proprietary computer programs. The LCC were estimated in millions of 1979 dollars for 750 aircraft with a 15 year life.

The First MCAIR Study (MCAIR-1) (17). The Air Force (AFWAL) hired McDonnell Douglas Corporation (MCAIR) in 1980 to determine the technology required to use CTFE fluid in aircraft while maintaining acceptable performance by keeping the weight penalty to a minimum (17). MCAIR used the RCA Price Cost Model and McDonnell Douglas' Advanced Concepts Cost Model in its analysis. An F-15C was chosen as the baseline aircraft using the following ground rules:

1. Costs were in 1982 millions of dollars.
2. Number of aircraft used was 500.
3. Software costs were included.
4. Support equipment was not costed.
5. Operational life was 15 years.
6. Annual flying hours per aircraft was 300 hours.
7. All three theatres were included for operational deployment.
8. Seven base-intermediate maintenance locations were figured into the estimate (17:250).

The Second MCAIR Study (MCAIR-2) (6). Later (in 1985) MCAIR selected the F-15 SMTD for a low energy program to design and test concepts which reduce heat rejection and weight in an 8000 psi nonflammable (CTFE) hydraulic system. The F-15 SMTD was chosen due to its assumed similarity to the next generation fighter. The study produced weight comparisons between CTFE and Mil-H-83282 at 3000 and between the two fluids at 8000 psi. The LCC comparisons were between Mil-H-83282 and CTFE at 3000 psi and between 3000 and 8000 psi using CTFE. The ground rules were similar to the F-15C study except the dollar savings were in 1985 dollars.

How These Studies Were Used. The Grumman study was used only for reference with regard to the effect of using Mil-H-83282 at 8000 psi. It was also used as a reference for the MCAIR-1 study. The Grumman study, however, could not be used directly in this analysis because of differences in aircraft and cost models. The latter problem could not be resolved due to the proprietary nature of the cost models.

The MCAIR-1 study calculated the weight and LCC of the F-15C hydraulic system at 3000 psi using Mil-H-83282 and at 8000 psi using CTFE. The weight of the F-15C aircraft and its fuel consumption were used to determine the LCC cost of fuel of the different alternatives (17).

The MCAIR-2 study on the F-15 SMTD estimated the differences in weights between an 8000 psi, Mil-H-83282 system and an 8000 psi, CTFE system. This is the only direct comparison done in any of the studies. Therefore, the weight difference was used in the LCC of fuel for the CTFE system in comparison to the Mil-H-83282 system (6).

All the studies provided information on the benefits, weight savings and LCC savings using 8000 psi. They, also, described the new developments needed to correct minor concerns in using 8000 psi and CTFE.

Life Cycle Costs. Table 6 lists the different categories concerning aircraft production which pertain to this analysis including a separate breakout for the cost of fires. Since decision makers need to be concerned with only those costs which are impacted by their decisions, only the LCC categories affected by the decision of which hydraulic fluid system to use will be addressed. The remaining categories which will not be directly addressed are either sunk costs or wash costs. Sunk costs are costs which are presently unavoidable. Wash costs are costs which are equal or almost equal between the alternatives. The sunk costs and wash costs will be identified but will not be included in the estimates of each alternative.

The LCC costs of using a nonflammable fluid versus a limited flammable fluid at 8000 psi are estimated on 500 aircraft with an operating life of 15 years. The

TABLE 6. USAF AIRCRAFT LIFE CYCLE COST CATEGORIES (16:86)

Research and Development

Investment

- System Investment
- Support Investment
  - Support Equipment
  - Initial Spares & Parts
  - Facilities
- War Reserve Material

Operating and Support

- Deployed Unit Ops
  - POL
    - Fuel Costs
    - Fluid Costs
- Below Depot Maintenance
- Depot Maintenance
- Personnel Training & Support
- Sustaining Investments

Total of Life Cycle Costs (Exclusive of Fires)

Cost of Fires

Research and Development

Investment

- Cost of New Aircraft
- Cost of New Components
- Cost of New Pilots

Operating and Support

- Fire Prevention
- Additional Maintenance
- Training
- Additional Support
- Injuries and Lives

Total Life Cycle Costs of Fires

Grand Total of Costs Involved

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costs are in 1987 dollars and use the F-15C as the proxy aircraft.

Research and Development Costs. Under the research and development costs category in Table 6, all of the costs for each alternative are considered sunk costs because most of the development and research expense has been either incurred or is under contract. For example, the Aero Propulsion Laboratory has just recently hired MCAIR to "develop and demonstrate 8000 psi nonflammable hydraulic system technology for advanced fighter aircraft" (21) including technology developed from previous programs using 8000 psi. The completion date is projected to be in 1990, which is the same time period as the full scale development for the ATF (21).

Investment Costs. Under the investment costs category and its sub-category system investment, both of the alternatives would incur costs based on the number of aircraft produced and costs associated with the use of an 8000 psi system. However, Alternative 2 would have additional costs related to using CTFE.

The MCAIR-2 study using the F-15 SMTD discussed the comparison of the weights of Mil-H-83282 and CTFE systems at 3000 and 8000 psi. At 8000 psi, the CTFE fluid system weighs 95 pounds more than the Mil-H-83282 fluid system (1,693 - 1,598). This study stated that this figure could be reduced to 70 pounds if the system is optimized for CTFE. This reduction showed that the CTFE weight problem can be reduced by 71 percent (from 243 to 70 pounds) operating the hydraulic system at 8000 psi instead of 3000 psi (6).

This weight penalty, in terms of aircraft purchase cost, is miniscule for a fleet of 500 aircraft, four hundredths of one percent ($11.6M/$28,396M). The initial investment cost would just be the cost of the fluid. Thus, the increase in costs would be the difference in the prices of the fluids ($100 - $9) multiplied by the 500 aircraft and the 9.7 gallons of fluid used per aircraft (6;17). The result of this equation is approximately $450,000.

Only certain areas under <u>support investment</u> would be affected by the choice of hydraulic system. These costs were estimated in the MCAIR studies and in their work on ground support equipment (6;17;22). Since the choice of fluids will not significantly affect these costs (support equipment, initial and war reserve spares and parts, facilities, and documentation), they are considered wash costs.

<u>Operating and Support Costs</u>. With regard to Operating and Support Costs, the significant differences between Mil-H-83282 and CTFE are in the categories of hydraulic fluid costs and POL (Petroleum, Oil and Lubrication) costs. Alternative 1 (Mil-H-83282) would require less

fuel due to lighter weight of its hydraulic systems and aircraft. Alternative 1 would also use an hydraulic fluid which is ten times cheaper than CTFE.

Hydraulic fluid expense is incurred based on the replacement of fluids due to leaks or normal repairs. Using an assumption that the loss is 10 percent per year, the annual cost would be $45,000 more for Alternative 2. To project the cost for the life of the aircraft in current year dollars, this value must be multiplied by a present value factor which uses a discount rate of 10 percent for 15 years or 7.606 (20). The result of this calculation is an estimated present value cost of $350,000.

The fuel expense is calculated by using the fuel consumption rate per flying hour of an F-15C (proxy aircraft) which is 1624 gallons, and then dividing it by the gross weight of the F-15C listed in the MCAIR-1 study, 44,520 pounds, in order to get the fuel consumption per pound per hour. The result of this division (0.0365) is then multiplied by 500 aircraft, 300 flying hours, the range of takeoff weight differences between the two systems (260 to 350 pounds), the price per gallon of jet fuel (JP-4, $.73), and the same discount factor (10 percent for 15 years, 7.606). These calculations produce a cost range of $7.9 to $10.6 million in FY 87 dollars (10;20).

The maintenance material for depot maintenance and below depot maintenance would include the same basic costs for each alternative. Personnel training and support, and sustaining investments would also be wash costs.

Operating and Support Costs Summary. The use of CTFE would increase the investment costs and operating and support costs. An estimate can be projected by using differences in the weight and the LCC of each fluid from the F-15C and F-15 SMTD studies (6;17). This estimate is summarized in Table 7.

Table 7. Change in Aircraft System Life Cycle Cost Analysis as a Result of Using CTFE (Millions of FY 87 Dollars)

Cost Category		CTFE & 8000 psi
Development		SUNK COSTS
Investment		.45
Operating & Support		10.95
Fluid	.35	
Fuel	10.60	
Total		$11.40

Life Cycle Cost of Fires. The life cycle cost of fires is only a concern with the use of Mil-H-83282 hydraulic fluid. Therefore, to determine the fires which involved Mil-H-83282 required the selection of an aircraft type which used it on an 100 percent basis. Mil-H-83282 is currently only used in tactical aircraft in the Air Force. This fluid is used on an attrition basis and the mixture of Mil-H-5606 with Mil-H-83282 reduces the latter's fire resistance. According to Technical Order 42B2-1-3, Fluids for Hydraulic Equipment, dated 1 November 1986 (12), with only 10 percent of the fluid being Mil-H-5606 the flash point of the overall fluid is reduced from 445° F to 330° F. The technical order also listed the various aircraft and suggested percentage of Mil-H-83282 fluid:

1. A-10 should use 95% minimum of Mil-H-83282;
2. F-15 should use 100% Mil-H-83282;
3. F-16 should use 100% Mil-H-5606 (According to HQ TAC, F-16's are now 100% Mil-H-83282 (25));
4. A-7D, F-4, F-5, and E/F-111 should use 90% minimum of Mil-H-83282

According to a list of fires by aircraft (13), the majority of the tactical aircraft hydraulic fires occurred on F-4's and F-16's. Only two occurred on F-15's. So the high cost of hydraulic fires can be attributed to Mil-H-5606 and the reduction in hydraulic fires over the past few years to Mil-H-83282. Thus, the usefulness of Mil-H-83282 in preventing fires seems evident but the savings cannot easily be determined in terms of dollars (13;14).

In order to estimate the LCC of a fire, the research and development, investment, and operating and support costs are addressed. First, the research and development costs are considered sunk costs. Second, investment costs were estimated from the historical data provided by the Air Force Inspection and Safety Center (AFISC) (13).

Finally, operating and support costs include costs which were incurred but not included in the historical data.

Investment Costs. As stated earlier, the total cost of Mil-H-83282 fires cannot be confidently quantified. The only dollar costs of fires available is the AFISC historical data which only includes estimates of the damage or loss, which are investment costs. Therefore, an average cost of all hydraulic fires involving the use of Mil-H-83282 fluid since its introduction in 1980 will be used as the investment cost of each fire attributed to Mil-H-83282. This calculation include all classifications of fire, from incident to major, and all types of hydraulic fluids. This average cost is $.5 million.

Thus, using historical data on the incidence of fires in aircraft using Mil-H-83282 hydraulic fluid approximately 7 fires can be expected over the 15 year life of a fleet of 500 aircraft (13;14). This figure times the average cost per fire equals the estimated investment cost of fires when using Mil-H-83282, $3.5 million in then year dollars. The present value of these dollars is calculated by using the average cost per fire times the average occurrence (7/15) times the discount rate (7.606). The result of this calculation is an estimated present value cost of fires of $1.8 million.

However, there are other investment costs not tracked which are incurred when a fire occurs. One such investment cost involved in a fire is the replacement of a pilot who dies in a plane crash caused by the fire. Assuming one pilot will die over the life of the fleet of aircraft, the cost of training another pilot to replace the one lost would be the investment cost. According to AFR 173-13, it costs $1.7 million to train an F-15C pilot (10). In order to keep all costs in present value terms, the death is assumed to occur at the midpoint of the 15 year operational life of the aircraft. Thus the present value of training one pilot over the operational life of the aircraft is $.9 million. Therefore, the total present value of the investment costs related to fires is $2.7 million. However, another factor which cannot be calculated is the lost experience or knowledge of the dead pilot. This factor would make the investment costs even higher.

Operating and Support Costs. Under the operating and support category, costs related to fires would include additional fire prevention services, extra work by maintenance personnel, loss of training, and loss of the services of related personnel due to injuries or death. The additional fire prevention services include the use of fire extinguishers or fire department equipment and personnel. The extra work by maintenance personnel would involve the repair and/or replacement of components. The fire would also require additional paperwork to be processed. Another important cost which cannot be put into dollars is the cost of lives or injuries to the maintenance crew or fire crew when a fire occurs, as well as injuries to the pilot.

Summary of the Life Cycle Costs of Fires. Although it is difficult to assess all of the costs of fires, the costs of repairs or replacement has been estimated by using information on the average cost of fires since 1980. These costs are added to those of Table 7 in order to arrive at an estimate of the grand total LCC cost impact of using CTFE. The results are shown in Table 8.

TABLE 8. Summary of Changes in Life Cycle Costs as a Result of Using CTFE (in millions of FY87 dollars)

Research and Development	Sunk Costs
Investment	+ $ .45
Operating and Support	+ 10.95
Sub-Total of Life Cycle Costs	+ $11.40
Cost of Fires	
Research and Development	Sunk Costs
Investment	- $ 2.7
Operating and Support	Not Available
Sub-Total Life Cycle Costs of Fires	- ($2.7 + O&S)
Grand Total of Costs Involved:	An increase of less than $8.7

IV. Sensitivity Analysis and Conclusions

This chapter will test the sensitivity of the information developed in Chapter 3 for peacetime and wartime scenarios. Also, other major uncertainties involved in the information will be examined and conclusions will be made with regard to the use of CTFE.

Peacetime Environment

The historical data, the cost models, and the information in the last chapter pertained primarily to a normal or peacetime environment. The differences in the Grand Total LCC of the alternatives is estimated to be not more than \$8.7 million in FY87 dollars. However, the measurement of the alternatives cannot be limited to the LCC but must include the benefits of each as well. Table 9 will provide a guide to the discussion of the two alternatives. Each area will be addressed separately.

Sensitivity Analysis of Peacetime Life Cycle Costs Estimates. The initial analysis determined that the main cost differences between CTFE and Mil-H-83282 are in weight and proclivity to fires. Therefore, the assumptions related to these categories crucially affect the LCC estimates. With regard to weight, the MCAIR-2 study stated that the weight difference using the two fluids in an F-15 SMTD will be between 70 and 95 pounds. The same study also stated the

Table 9. Comparison of Peacetime Differential Costs

Cost Category	Alternative 1 (8000 psi & Mil-H-83282) vs Alternative 2 (8000 psi & CTFE)
LCC	Alt 2 would cost $11.4 million more
Cost of Hydraulic Fires	Alt 1 would cost at least $2.7 million more
Benefits	Alt 2 would be slightly greater than Alt 1

weight difference was only caused by the density of the fluids themselves. The hydraulic system and aircraft design would be basically the same (6). The assumed weight difference causes an added present value cost of close to $12 million in fuel for 500 aircraft over 15 years. That equates to approximately $3200 (undiscounted) a year per aircraft, or the saving of less than one aircraft. If this value was considered an insurance premium on a $48 million aircraft (LCC), this would be acceptable. The use of CTFE is insurance against future hydraulic fires.

The use of 8000 psi has been assumed in all the calculations so far but it is interesting to consider the impact the use of 3000 psi would have on the results. The MCAIR-2 study stated that CTFE weighs an additional 900 pounds in takeoff weight at 3000 psi. The investment costs would include any added structural requirements for the additional weight and the added cost of the initial fluid at 25 gallons per aircraft or an approximate $1.5 million. Using the same formula as in the 8000 psi case, the operating and support costs at 3000 psi are estimated to be $28.3 million in present value FY87 dollars. The additional LCC of using CTFE at 3000 psi (excluding fires) in relation to Mil-H-83282 is approximately $30 million in present value FY87 dollars or approximately $7900 (undiscounted) a year per aircraft.

Life Cycle Cost of Fires. With regard to fires, the estimates of cost savings based on the nonflammability of CTFE are limited in accuracy by two weaknesses found in the historical data base on fires.

First, approximately 90 percent of the fires for which information is available involved Mil-H-5606 fluid (14), the most flammable of the fluids in use today. The remainder of the fires involved Mil-H-83282 or a combination of Mil-H-5606 and Mil-H-83282. The F-15 and the F-16 have used Mil-H-83282 at 100 percent only since 1984 and 1986 respectively.

Second, the estimated costs do not include all the costs incurred when a fire occurs. These other costs would increase the total costs of even the slightest fire. These costs include: additional maintenance, additional fire protection support, additional administrative support, and loss of personnel through injury (temporary loss) or death. The

Air Force pays for all of these expenses but they are not identified with each fire incident. Therefore, the estimated cost of fires is most likely the minimum of the costs involved (13;14).

Sensitivity of Peacetime Benefits. The peacetime benefits were summarized in Table 5. The use of nonflammable CTFE improves the availability, reliability and survivability of the aircraft and aircrews. On the other hand, its added weight reduces aircraft capabilities slightly. However, if CTFE were used at 3000 psi the takeoff weight would increase by 900 pounds compared to 350 pounds at 8000 psi and as a result capability might be significantly affected.

Wartime Environment

The analysis so far has only estimated the benefit and cost differences in peacetime. However, the primary mission of the aircraft is to fight a war. Therefore, the impact of a combat situation on costs and benefits needs to be considered. This analysis will start with the LCC excluding fires, then cover the cost of fires, and finish with the benefits.

Sensitivity of Wartime Life Cycle Costs. In a war, the differences in LCC of a hydraulic system excluding fires will change from the peacetime cost because the operating and support costs would include the added fuel consumption based on additional flying hours and added hydraulic fluid replacement due to damage or additional maintenance actions. The investment costs unrelated to hydraulic fire damage would not change.

Life Cycle Costs of Fires. The LCC of fires in a war would increase the cost of using Mil-H-83282 in relation to CTFE due to the substantially increased probability of an hydraulic fire. Currently, a hydraulic fire occurs due to mechanical failure. In a battle, hydraulic fluid fires would increase in the presence of hostile gunfire. Gunfire can inflict damage to an aircraft's fuel or hydraulic system. Therefore, the leaks caused by this damage can be ignited by the hot surfaces in the engine bay area or by the gunfire itself, since some are incendiary devices. The increase in costs would be under investment and operating and support categories.

Investment Costs. The investment costs would drastically increase in a war. The number of aircraft lost would increase because aircraft on fire may either be abandoned (pilot ejecting from the aircraft), or land in enemy territory. The number of pilots lost would increase due to death and to capture when landing in enemy territory.

Operating and Support Costs. The operating and support costs related to fires would require the replacement of components more frequently than normal maintenance. However, the supply of components in a war would be limited. Once the initial supply is exhausted, resupply may take valuable time. Therefore, the aircraft will either have to wait for parts or other damaged aircraft will have to be cannibalized to keep as many aircraft flying as possible. Both of these actions reduce the number of assets available to fly and fight the war.

Maintenance and repair actions related to hydraulic fire damage would also increase the possibility of maintenance errors caused by the increased activity involved in a war. Errors such as not tightening a bolt properly are one of the common causes of fires in the past (13;14). The war atmosphere would probably increase this type of fire.

The Benefits. The peacetime benefits comparison estimated the differences between the fluids to be slight. However, in a wartime scenario, the benefits of using a nonflammable fluid such as CTFE could be of great significance. As stated before, the main benefits involved in the decision on which hydraulic fluid to use are availability, reliability, capability and survivability.

Availability. The availability of aircraft would be critical. The use of CTFE would eliminate the logistical and operational problems related to hydraulic fires. The need for cannibalization and additional maintenance actions would be greatly reduced.

Reliability. The reduction in maintenance actions will also improve the reliability of the system. The maintenance personnel will have the necessary time to prevent mistakes. Also, the equipment will follow its normal wear cycle without the interference of the maintenance crews tearing down an aircraft to keep another aircraft flying.

Capability. The weight of CTFE would slightly impair aircraft capabilities by limiting the amount of equipment and/or munitions which could be carried. On the other hand, the increased availability of aircraft and the increased probability that the aircraft will return safely will improve the battle capabilities of military aviation as a whole. For example, a battle plan which requires air support in several locations at once may have to wait until the necessary aircraft are available although the need to implement this plan is time critical. Thus, the war could be lost due to the delay.

Survivability. The survivability benefit of CTFE is attributable to the prevention of fires caused by gunfire and leaks. This prevention could allow a pilot to land a damaged aircraft in friendly territory, saving the pilot and aircraft so that they may fight again. The saving of these assets can improve the chances of winning a crucial battle or the entire war.

Additional Sensitivity Factors

Any research of this kind involves some uncertainties and these uncertainties must be considered in order to appreciate the sensitivity of this analytical results. Some of the major uncertainties involved in the analysis are the price of fuel, the fluid replacement rate, the discount rate, and hydraulic pressure. The LCC discussed in the following areas pertains to the present value cost of Grand Total LCC assuming a discount rate of 10 percent unless otherwise stated.

Price of Fuel. The price of fuel is currently 73 cents a gallon; however, the price was 93 cents in 1985 (10). At 93 cents, the additional Grand Total LCC with the use of CTFE would increase from $8.7 million to $11.6 million at 8000 psi. At $1.25 a gallon (arbitrarily selected) the additional LCC is $16.3 million at 8000 psi.

Fluid Replacement Rate. The calculations have assumed a 10 percent replacement of hydraulic fluid per aircraft per year. To test this assumption for sensitivity, 20 percent and 0 percent were chosen. At 8000 psi the Grand Total LCC cost would increase from $8.7 to $9.05 million at 20 percent and decrease to $8.35 million at 0 percent. Therefore, the fluid replacement rate is relatively unimportant.

Discount Rate. The discount rate used in all the foregoing calculations is 10 percent based on AFP 178-8 (11). However, to test the sensitivity of the results to this discount rate, two other discount rates are considered: Assuming a 5 percent discount rate the present value cost of Grand Total LCC for 8000 psi increases from $8.7 million to $13 million; assuming a 15 percent rate the Grand Total LCC decreases from $8.7 million to $6 million.

Hydraulic Pressure. As stated earlier, the assumed pressure for future hydraulic systems is 8000 psi, but the current pressure of tactical aircraft is 3000 psi. Table 10 shows the possible changes in the Grand Total present value LCC with regard to the use of CTFE in fighter aircraft at these two different pressures. The largest change is in the category of operating and support costs. This change is

TABLE 10. Sensitivity of Benefits/Costs Estimates to Hydraulic Fluid Pressure Attributable to CTFE (in millions of FY87 dollars)

	3000 psi	8000 psi
Investment	+ $ 1.5	+ $ .45
Operating and Support	+ 28.3	+ 10.95
Sub-Total of Life Cycle Costs:	+ $29.8	+ $11.40
Cost of Fires (Excluding O&S)	- $ 2.7	- $ 2.7
Grand Total of Costs (10% Disc Rate):	+ $27.1	+ $ 8.7
Discount Rates: 5%	$38.0	$13.0
15%	20.0	6.0
Price of Fuel: $1.25	46.6	16.3
.93	34.6	11.6
Fluid Replacement Rate: 20%	27.9	9.05
0%	26.3	8.35
Benefits of CTFE		
Availability	Better	Better
Reliability	Better	Better
Capability	More Negative	Negative
Survivability	Better	Better

caused by the increase in the size of the system and the amount of fluid needed at 3000 psi. This added fluid, 25 gallons versus 9.7 gallons, increases the weight impact of CTFE which in turn increase the takeoff weight and the fuel consumption of the aircraft. Moreover, the added weight further reduces the capabilities of the aircraft by further limiting the amount of equipment and/or munitions which the aircraft could carry.

Worst Case/Best Case

A range of peacetime costs based on the worst and best cases of the variables in Table 10 is provided to assist the decision maker. The worst case is when the fuel price is $1.25 a gallon, the hydraulic fluid annual replacement rate is 20 percent, and the discount rate is 5 percent. The best case is when the fuel price is $.73 per gallon, the fluid replacement rate is 0 percent, and the discount rate is 15 percent. Moreover, the additional takeoff weight for using CTFE used in these calculations is 350 pounds at 8000 psi and 900 pounds at 3000 psi for both worst and best case situations. Thus, the range of costs at 8000 psi is from $5.7 to $23.2 million and the range at 3000 psi is from $19.3 to $66.2 million. These dollars are the Grand Total LCC in present value FY87 dollars. The benefits, on the other hand, remain approximately equal except the capability of aircraft using CTFE will decrease at 3000 psi due to the additional weight.

Other Sensitivity Factors

Use of CTFE Outside the United States. Since CTFE is new to the aircraft industry, its supply and demand has been limited to the testing facilities within the United States. However, tactical aircraft are stationed outside this country and in a war might use forward operating locations which will need to have CTFE available. Therefore, the use of CTFE in the next generation of tactical aircraft could present logistical problems within and outside the United States.

The largest source of this foreign use problem will come from Europe since none of their aircraft or airfields will have this fluid. To solve this problem and that of forward operating locations, the Air Force could preposition supplies at these locations to be used in emergencies or war. However, this plan requires large amounts of current money to be spent in case of need in the future. Also, the fluid may not be able to be stored for long periods of time without the need for replacement.

Cost Models. Various LCC estimates related to 8000 psi and the two fluids were available in defense contractors' studies but those studies did not address the problem considered in this thesis directly. Therefore, a number of assumptions had to be made: First, it was assumed that the estimates provided by these cost models were accurate. The cost models involved were proprietary and thus the estimated relationships between pressure, weight and costs are not independently verifiable. Second, the cost models calculated the costs of developing an 8000 psi hydraulic system for future tactical aircraft assuming that an F-14 and F-15 are analogous to future systems. Third, since the studies did not investigate the relationship of changes in weight to changes in cost, it is necessary in this thesis to assume a linear relationship. Fourth, the cost models also assumed a particular support operation and method of allocating support costs which may or may not be representative of future operations. Finally, these studies did not include the cost of ground support costs nor any discussion of fires.

Conclusions

The next generation of aircraft will involve the use of new technology. The use of 3000 psi is a perfect example of the technology which can improve the capabilities of the Air Force directly. Indirectly, the use of 3000 psi presents an unique opportunity to use a nonflammable hydraulic fluid like CTFE. The 8000 psi pressure reduces the weight penalty and LCC of CTFE. Therefore, based upon the analysis contained in this thesis, the use of CTFE in future aircraft seems very attractive. In comparing the two hydraulic fluids, cost savings alone would justify the use of CTFE versus Mil-H-83282 if one aircraft is saved from being destroyed by fire at 8000 psi and if approximately two aircraft are saved at 3000 psi. However the real advantage of

CTFE becomes more apparent in a combat situation. The increase in survivability attributable to CTFE could produce increases in mission effectiveness which could be of much greater value than the cost savings from fewer fires. Nonetheless, the decision on which fluid to use would benefit from a more complete evaluation of Mil-H-83282 and CTFE.

In looking to the future, a more complete evaluation on the subject of this thesis can be accomplished with further research on how well Mil-H-83282 has prevented fires. Further research should also be conducted on the logistical problems which may occur using 8000 psi and CTFE, as this may significantly increase the costs related to their use.

Appendix: Glossary of Technical Terms

1. Accumulators store the fluid under pressure. If the system's pressure decreases below the pressure holding the fluid in the accumulator, then the fluid is released into the system under pressure. Accumulators also supply fluid for temporary demands greater than the pumps can supply (18).

2. Actuators: The primary hydraulic system motors are cylindrical actuators which provide or develop a straight line motion. These actuators are called linear actuators. Actuators can be balanced, unbalanced or partly balanced in terms of fluid used in extension versus retraction of the rod within the cylinder (18).

3. Autogenous Ignition Temperature (AIT). This temperature is considered to be the minimum for a fluid to ignite in a test apparatus without an external ignition source (26:706). "The primary usefulness of the test is to furnish a relative rating scale, rather than produce absolute values which can be directly applied to problem solutions (1:5)."

4. Availability is the percentage of time the aircraft is in service or available for service.

5. Connectors performs three tasks: the connector must join to the tubing in a firm, leakproof manner; must carry any loads or stresses imposed on it by the hydraulic system or by the tubing, and; must provide a seal between the part being joined (18:81)." Two primary groups of connectors are separable and permanent. The former includes at least one joint which can be removed and attached easily (18).

6. Control devices include relief valves, pressure control valves and flow control valves (18).

7. Elastomers act as both solid materials and as very high viscosity fluids. Under pressure they flow and deform until internal stresses equal the external. This flowing action is similar to the flow of highly viscous fluids (18).

8. Flow Control Valves perform two primary functions: direct the flow of fluid from power generating devices and distribution systems to power transducers and they

use the systems pressure to restrict the fluid flow. Two types of these valves are shutoff and modulating valves (18).

9. Fire Point is the minimum temperature which the bulk oil must attain for ignition and continued burning in a test apparatus (26:706).

10. Flame Propagation Test. "This is an experimental method to determine differences in flame-propagation characteristics of aerospace hydraulic fluids. These differences can be the determining factor whether an aircraft is totally lost or merely slightly damaged (26:707)."

11. Flash Point is the minimum temperature that the bulk fluid must attain to generate sufficient vapor to be ignited by a low-energy flame in a test apparatus. (26:706)

12. Gunfire Resistance Test. The method consists of the shooting of 50-caliber armor-piercing incendiary ammunition into partially filled aluminum canisters of the test fluid. Five shots are fired and the number of ignitions and severity of the subsequent fires are reported (26:706-707).

13. Halogenated Oils are several types of hydraulic fluids which offered the desired degree of fire resistance were analyzed. These oils, however, are not compatible with hydrocarbon oils because of the differences in their physical and chemical properties (28).

14. Heat Exchangers are used to remove the excess heat from the system before damage can occur (18).

15. Heat of Combustion Test. This test measures the heat generated by a fluid during combustion once ignited and is a significant factor in the flame propagation characteristics of a fluid. "The higher the heat of combustion, the greater the energy released into the bulk fluid. This increases the fluid temperature and makes it more easily ignited (26:706)."

16. Hydraulic System: The system provides power to operate primarily the aircraft's flight controls, as well as, other areas. The system itself can be divided into four areas: power input unit, power distribution system, control devices and power output unit (18).

17. Hydrocarbon Oils are several types of hydraulic fluids currently used in military aircraft. These oils include Mil-H-5606 and the synthethic Mil-H-83282.

18. Power Distribution System is comprised of reservoirs, tubing, connectors, filters, and seals (18).

19. Power Input Unit involves pumps and accumulators (18).

20. Power Output Transducers is the final part of the hydraulic system. This part consists of linear actuators, rotary or oscillating motors (18).

21. Pressure Control Valves are used to lower the pressure in a portion of the system to a desired level. Several types of pressure control valves include: pressure reducing valve, lack pressure regulators and differential pressure regulators (18).

22. Pumps are the primary source of power in the hydraulic system. Piston pumps are usually used in high-pressured systems, above 2500 psi (18).

23. Reliability is the "probability that a system or product will perform in a satisfactory manner for a given period of time under specified operating conditions (2)."

24. Relief Valves are usually used to limit pressure surges or to compensate for failed pump pressure controls (18).

25. Reservoirs provide fluid to make up for system leakage, allows space for expansion due to increases in temperature, allows gas bubbles to escape from the fluid and allows dirt to settle to the bottom (18).

26. Seals: There are three types of seals: static, dynamic and rotating. Static seals use a pressure level significantly higher than the system pressure they must contain to seal with their mating parts. Dynamic seals must withstand motion as well as contain the systems pressure. Rotating seals are used around a rotating shaft. "A combination of pressure and spring force causes two carefully mated parts to bear on each other with relative rotary motion and create a very fine fit (18:145)."

27. Shearing Stress "is an action or stress resulting from applied forces that causes or tends to cause two continguous parts of a body to slide relatively to each other in a direction parallel to their plane of contact (32)."

28. Skydrol is a phosphate ester hydraulic fluid introduced in the 1950's into commercial aircraft.

29. Stream Hot-Manifold Ignition Temperature Test. This test is considered to simulate the fire hazard presented when a fluid comes in contact with a heated surface.

This ignition mode is of significant importance in aerospace applications, primarily hot brakes scenarios (26:706).

30. <u>Survivability</u>. The survivability of the aircraft is one of the most important attributes of CTFE. It is the ability of the aircraft to either complete a mission or return to base with damage or malfunctioning equipment.

31. <u>Takeoff Weight</u>. The assumption is for every pound added to a subsystem, the total takeoff weight of an aircraft is increased by 3.7 pounds (19).

32. <u>Viscosity</u> "is the property of a fluid or semifluid that enables it to develop and maintain an amount of shearing stress dependent upon the velocity of the flow and then to offer continued resistance to the flow (32)."

Bibliography

1. Aviation Fluids Flammability Group. Flammability of Aircraft Hydraulic Fluids - A Bibliography. CRC Project No. CA-49-71. Atlanta: Coordinating Research Council, Inc., January 1986.

2. Bazousky, Igor. Reliability Theory and Practice. Prentice Hall Inc., 1961.

3. Bickel, William N. and John Ohlson. Lightweight Hydraulic System Technology - 8000 PSI Update. SAE Technical Paper Series, no. 851910. Warrendale PA: Society of Automotive Engineers, Inc., 1985.

4. Bickel, William N. and Robert K. Haning. Fabrication and Testing of Lightweight Hydraulic System Simulator Hardware - Phase II. Contract N62269-80-C-0261. Columbus OH: North American Aircraft Operations, Rockwell International Corporation, January 1986 (AD-A169884).

5. Binns, K.E. and William B. Campbell. Personal Interview. Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson AFB OH, 13 April 1987.

6. ----- and others. Nonflammable Fluid and 8000 psi Technology for Future Aircraft Hydraulic Systems. SAE Technical Paper Series, no. 851909. Warrendale PA: Society of Automotive Engineers, Inc., 1985.

7. Campbell, William B. Business Correspondence. Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Aeronautical Systems Division, Air Force Systems Command. Wright-Patterson AFB OH, 27 June 1986.

8. Demarchi, Joseph N. and Robert K. Haning. Flight Test of An 8000 PSI Lightweight Hydraulic System (LHS). Contract N62269-76-C-0254. Columbus OH: Columbus Aircraft Division, Rockwell International Corporation, April 1977 (AD-A039717).

9. -----. Lightweight Hydraulic System Hardware Extended Endurance Test. Contract N62269-78-C-0005. Columbus OH: Columbus Aircraft Division, Rockwell International Corporation, September 1978 (AD-A062749).

10. Department of the Air Force. US Air Force Cost and Planning Factors AFR 173-13. Washington: HQ USAF, 2 September 1986.

11. Department of the Air Force. Economic Analysis Procedures Handbook AFP 178-8. Washington: HQ USAF, 19 May 1981.

12. Department of Defense. Fluids for Hydraulic Equipment. Technical Order 42B2-1-3. Washington: HQ USAF, 1 November 1986.

13. Directorate of Aerospace Safety, Air Force Inspection and Safety Center. "USAF Hydraulic Fluid Fires: 1965-1984" and 1986 update to this report. Report to Air Force Wright Aeronautical Laboratories. Wright-Patterson AFB OH, 1985.

14. Directorate of Aerospace Safety, Air Force Inspection and Safety Center. Fighter/Attack Hydraulic Fluid Fire Mishaps 1980 to Date. Wright-Patterson AFB OH, 29 Jan 1987.

15. Encyclopedia of Aviation, New York: Reference International Publishers Limited, Charles Scribner and Sons, 1977.

16. Gill, Leroy. Class Handouts distributed in AMGT 559, Life Cycle Costing. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, 1986.

17. Jeffery, J. R. and others. Flight Worthiness of Fire Resistant Hydraulic Systems. Contract F33615-80-C-2074. St. Louis MO: McDonnell Douglas Corporation, 15 December 1984 (AD-A156618).

18. Keller, George R. Hydraulic System Analysis (Second Edition). Cleveland: Industrial Publishing Company, 1974.

19. Kinzig, William. Personal Interviews. ATF Systems Program Office, Aeronautical Systems Division, Air Force Systems Command. Wright-Patterson AFB OH, 27 May and 10 August 1987.

20. Naval Facilities Engineering Command. Economic Analysis Handbook NAVFAC P-442. Alexandria VA, June 1986.

21. "Nonflammable Hydraulic Power System for Tactical Aircraft". Program Kick-off Meeting Notes and Handouts. Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories. Wright-Patterson AFB OH. 8 April 1987.

22. Pierce, Neil. Telephone Interview. McDonnell Douglas Company, St. Louis MO. 20 July 1987.

23. Raymond, E. T. "Design Guide for Aircraft Hydraulic Systems and Components for Use with Chlorotrifluoroethylene Nonflammable Hydraulic Fluids". Contract F33615-76-C-2064. Seattle WA: Boeing Military Airplane Company, March 1982 (AD-A112097).

24. ----- and others. "Fire Resistant Aircraft Hydraulic System". Contract F33615-76-C-2064. Seattle WA: Boeing Military Airplane Company, July 1982 (AD-A112097).

25. Schultz, William. Telephone Interview. Directorate of Logistics, Headquarters Tactical Air Command, Langley AFB VA, 5 June 1987.

26. Snyder, Carl E. Jr., Arthur A. Krawetz and Theodore Tovrog. "Determination of the Flammability Characteristics of Aerospace Hydraulic Fluids". Lubrication Engineering, 37: 705-714 (December 1981).

27. ----- and others. Nonflammable Aircraft Hydraulic System Development. SAE Technical Paper Series, no. 821566. Warrendale PA: Society of Automotive Engineers, Inc., 1982.

28. -----, Lois J. Gschwender, William M. Warner and George W. Fultz. Air Force Nonflammable Hydraulic System Materials Development. SAE Technical Paper Series, no. 851908. Warrendale PA: Society of Automotive Engineers, Inc., 1985.

29. -----, and Lois J. Gschwender. Personal Interview. Materials Laboratory, Air Force Wright Aeronautical Laboratories, Aeronautical Systems Division, Air Force Systems Command. Wright-Patterson AFB OH, 17 April 1987.

30. -----, Lois J. Gschwender, and William B. Campbell. "Development and Mechanical Evaluation of Nonflammable Aerospace -54^{o} to 135^{o} C Hydraulic Fluids". Lubrication Engineering, 38: 41-51 (January 1982).

31. Wallace, Michael. New Hydraulic Fluid Lowers Risks of Aircraft Fires. Unpublished Report to the Advanced Tactical Fighter Systems Program Office. Wright-Patterson AFB OH, 28 January 1986.

32. Woolf, Henry B., editor. Webster's New Collegiate Dictionary (Fifth Edition). Springfield MA: G & C Merriam Company, 1977.

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ABSTRACT

This study analyzed the life cycle costs, cost of fires, and benefits of using CTFE in future tactical aircraft versus Mil-H-83282 currently used in tactical aircraft. The study assumed that future hydraulic systems will use 8000 psi pressure. An analogy was made using a contractor's study, which compared Mil-H-83282 and CTFE at 8000 psi showing weight as the primary difference, as the basis. Therefore, this weight difference, the fluid price difference, and the fuel consumption of an F-15 were used to determine the life cycle cost difference between the two systems. Since the added weight was slight, only the additional fuel consumption to fly the extra weight was significant. The added life cycle costs for using CTFE was estimated at $11.4 million in FY87 dollars.

However, CTFE will prevent hydraulic fires so an estimate of Mil-H-83282 fire costs was attempted. These fire costs were difficult to accurately determine. The history of hydraulic fluid contained primarily fires caused by a highly flammable fluid (Mil-H-5606). Also, early fires involving Mil-H-83282 included Mil-H-83282 mixed with Mil-H-5606. Therefore, only a limited history on the true fire resistance capabilities of Mil-H-83282 was available. Also the available history failed to include several other costs which are incurred when the fire occurs.

The differences in the benefits were primarily in the survivability and capability of the aircraft. Taking these differences together CTFE is slightly better than Mil-H-83282 in peacetime. This difference becomes more pronounced in wartime.

Finally, a sensitivity analysis was conducted on the assumptions. Based on these analyses, a conclusion was made that CTFE was a viable alternative at 8000 psi. However, further research was needed on the logistical problems related to the new pressure and fluid. Also, further study was needed on the effectiveness of Mil-H-83282 against the causes of hydraulic fires.

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